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Experimental and numerical study of potassium chloride flow using smoothed particle hydrodynamics

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ABSTRACT

Materials in granular form are widely used in industry and in the society as a whole. Granular materials can have various behaviours and properties. An accurate prediction of their flow behaviour is important to avoid handling and transportation issues. In this study, the flow behaviour of dry potassium chloride (KCl) in granular form was investigated experimentally and simulated numerically. The aim was to develop numerical tools to predict the flow of KCl in transportation and handling systems and granular material flow in various industrial applications. Two experimental setups were used to quantify the flow of KCl. In the first setup, the collapse of an axisymmetric granular column was investigated. In the second setup, digital image correlation was used to obtain velocity field measurements of KCl during the discharge of a flat-bottomed silo. The two experiments were represented numerically using two-dimensional computational domains. The smoothed particle hydrodynamics method was used for the simulations, and a pressure-dependent, elastic-plastic constitutive model was used to describe the granular materials. The numerical results were compared to the experimental observations, and an adequate qualitative and quantitative agreement was found for the granular column collapse and the silo discharge. Overall, the simulated flow patterns showed adequate agreement with the experimental results obtained in this study and with the observations reported in the literature. The experimental measurements, in combination with the numerical simulations, presented in this study adds to the knowledge of granular material flow prediction. The results of this study highlights the potential of numerical simulation as a powerful tool to increase the knowledge of granular material handling operations.

1. Introduction

Potassium chloride (KCl) is a natural potassic fertilizer that is essential for the agricultural industry globally. KCl originates from potassium-rich minerals formed from evaporated seawater. The most important source for KCl is sylvinite ore, which contains a mixture of KCl and sodium chloride (NaCl). Ore deposits are typically mined in underground mines, and the ore is then processed to separate the KCl from the unwanted constituents. The separated KCl is then prepared for use as a fertilizer. It is screened and delivered to the end user as a granular material with a uniform particle size (British Geological Survey, 2011). After production, the KCl is subjected to a number of transportation and handling systems. Knowledge of the handling of KCl becomes important to ensure efficient transportation. Efficient loading and unloading operations result in shorter dwell times, which generate economic benefits. To study and optimize the transportation and handling systems, knowledge of the flow behaviour of granular materials is required. The scope of this study was to develop experimental and numerical techniques to predict the flow of KCl.

A granular material can be defined as any material composed of a large number of individual particles, regardless of the particle size (Nedderman, 1992). Thus, granular materials include a wide range of materials, from powders composed of fine particles to conglomerations of large rocks. Depending on the conditions, the granular material may behave as a solid, liquid, or gas (Jaeger et al., 1996). Quasi-static conditions typically result in behaviour similar to that of a solid, while granular material flow is similar to that of a liquid, and conditions of strong agitation result in a gaslike behaviour.

Granular materials are commonly used in industries, and the dynamic flow behaviour of granular materials is relevant in many processes. The complex behaviour of granular materials is poorly understood, and a unified theory for the mechanical behaviour of granular materials does not exist. Numerous experimental and numerical studies of granular materials can be found in the literature, and this area of research continues to attract attention. The collapse of granular columns under the influence of gravity was initially studied

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experimentally by Lube et al. (2004, 2005) and simultaneously by Lajeunesse et al. (2004, 2005). Their work revealed that the shape of the final granular material deposit was primarily dependent on the initial aspect ratio between the height and radius of the column. Furthermore, a centred and conically shaped static region was present during the collapse of the column for all investigated aspect ratios. In addition, the discharge dynamics of granular materials from silos and hoppers has been studied extensively. Silos and hoppers are widely used in the mining, pharmaceutical, and agricultural industries, where storing and handling of granular materials is important. Although granular material flow during the discharge of silos and hoppers has been studied experimentally by numerous researchers (see e.g. Pariseau, 1969; Nedderman et al., 1982; Tüzün et al., 1982; Michalowski, 1984; Chen et al., 2007; Mankoc et al., 2007; Albaraki and Antony, 2014), there is still a lack of unifying theories for granular material flow in silos and hoppers (Yang and Hsiau, 2001).

Granular material flow has traditionally been studied using analogue photography, where displacement was measured by tracking sample particles flowing through a system (see e.g.Pariseau, 1969; Michalowski, 1984; Takahashi and Yanai, 1973). The continued development of numerical methods for the simulation of granular material flow requires improved experimental methods and methods for high-accuracy field measurements of granular material flow. Flow field measurements are essential for the calibration and validation of numerical models. These are fundamental steps in the evaluation of the accuracy of numerical simulations. The introduction of digital photography has led to the development of optical techniques, such as the digital particle image velocimetry (DPIV) method (Willert and Gharib, 1991). The DPIV method enables field measurements by using a cross-correlation method on a series of digital images. This technique was applied by Sielamowicz et al. (2005) for field measurements of granular material flow during the discharge from plane hoppers. Digital image correlation (DIC) is an optical experimental technique that has been used extensively for the displacement and strain field measurement of materials subjected to large strains (Kajberg and Lindkvist, 2004; Pan et al., 2009). The DIC technique is based on the comparison of a series of digital photographs of a specimen surface recorded during deformation. Similar to the DPIV technique, a cross-correlation procedure is applied to determine the in-plane displacement field. In Larsson et al. (2016), the DIC technique was used to study and characterise granular material flow through field measurements.

For the numerical study of granular material flow, there are two main approaches. The first is to use a discrete micro-mechanical approach. In the discrete element method (DEM), originally formulated by Cundall and Strack (1979), each grain in the granular material is modelled with a corresponding discrete, usually spherical, particle. The particles are considered to be rigid; however, a small overlap is allowed at contact between particles. A contact law that relates the overlap to the contact force is applied, and the motion of the granular mass is governed by Newton's second law of motion. In the literature, a number of variations of granular column collapses have been simulated with the DEM. Initially, the collapse of granular columns was simulated using two-dimensional implementations of the DEM (see e.g. Staron and Hinch, 2005, 2007; Zenit, 2005; Lacaze et al., 2008). Recently, three-dimensional implementations of the DEM have been used to simulate the collapse of prismatic (see e.g. Girolami et al., 2012; Utili et al., 2015) and cylindrical granular columns (Kermani et al., 2015). In the literature, there are numerous studies where the discharge of granular material from silos and hoppers was modelled using three-dimensional implementations of the DEM, see Balevičius et al. (2011) and González-Montellano et al. (2011, 2012). The research groups used the DEM with spherical particles. Recently, implementations of the DEM with additional particle shapes have attracted attention. In Liu et al. (2014), flat-bottom hopper discharge was simulated using ellipsoidal particles.

The literature contains promising results from discrete methods to simulate granular material flow; however, for the simulation of field-scale events, the use of discrete methods is impractical. The computational cost increases with an increasing number of particles, and this is a drawback of the discrete approach. It is common to use size scaling, where the size of the DEM particles is increased while the problem domain remains at the same size. This could reduce the required number of particles to a computationally feasible level; however, it then becomes necessary to assess how accurately the model represents the physical problem. The values of the parameters required for discrete modelling of granular materials are difficult to obtain. A numerical calibration of the micro-mechanical parameters, such as the contact stiffness, contact damping, and sliding and rolling coefficients of friction, is required to represent the experimentally measured macro-mechanical behaviour of the granular material.

The second main approach to model granular materials is to use a continuum approach. Modelling of granular materials with a continuum approach does not require the modelling of individual particles and their interactions. Conversely, the granular material is treated as a continuous substance, and a constitutive law relating the stresses and strains is used to represent the macro-mechanical properties. The macro-mechanical properties can be directly obtained through laboratory tests. A major advantage of using a continuum approach is that the problem can be discretized using a length scale larger than the size of the individual particles. Thus, a large number of particles can be treated without excessive computational cost. The finite element method (FEM) has a long tradition in the continuum mechanics field, see for instance Zienkiewicz et al. (2013) for a detailed description. The FEM has been used to simulate problems from a variety of technical disciplines, including the simulation of granular material flow. The FEM can be used with a Eulerian or a Lagrangian description of motion. For a Eulerian description, the analysis is performed with a stationary mesh; thus, mesh distortion is avoided in large deformations. However, there are drawbacks, including difficulties in handling free surfaces and moving boundaries. In Karlsson et al. (1998), Elaskar et al. (2000, 2007) and Zheng and Yu (2015), the FEM with a Eulerian approach was used to simulate granular material flow. A Lagrangian description of motion, where the mesh moves with the material, facilitates the modelling of free surfaces and moving boundaries. However, for large deformations, the mesh may become distorted, resulting in numerical difficulties. There are additional methods where combinations of Eulerian and Lagrangian descriptions are used to include the advantages from both methods. These methods were applied in the studies by Crosta et al. (2009, 2015), where the column collapse was simulated, and by Wang et al. (2013) for simulating granular material flow during hopper discharge.

In addition to the FEM, there are a number of other continuum-based methods that have been applied to model granular material flow. The particle finite element method (PFEM) was originally developed for modelling fluid flow and fluid structure interaction (Idelsohn et al., 2003, 2004). The PFEM has been used to model processes from a variety of engineering disciplines, including granular material flow (see e.g. Zhang et al., 2013, 2014; Cante et al., 2014; Dávalos et al., 2015). The smoothed particle hydrodynamics (SPH) method is a Lagrangian mesh-free method, where particles are used to represent the computational domain. In the SPH method, connectivity between the individual particles is not required. Because it is a mesh-free method, the SPH method can be used to treat large deformation while avoiding the numerical difficulties due to mesh distortion that are associated with mesh-based methods. In the literature, the SPH method has been used to model granular material flow during the collapse of granular columns (see e.g. Chen and Qiu, 2012; Minatti and Paris, 2015; Peng et al., 2015, 2016; Ikari and Gotoh, 2016) and silo discharge (Gustafsson et al., 2007).

In this study, the flow of two types of KCl with various particle sizes and shapes was experimentally and numerically studied. Two cases, which featured different flow mechanisms, were investigated: the axisymmetric granular column collapse and the discharge of granular